Moore, P.A., Jr. and D.M. Miller. 1994. Decreasing phosphorus solubility in poultry litter with aluminum, calcium and iron amendments. J. Environ. Qual. 23:325–330.
Paul, E.A., and F.E. Clark. 1996. Dynamics of residue decomposition and soil organic matter turnover. p. 174. *In* Soil microbiology and biochemistry. 2nd ed. Academic Press, San Diego, CA.
SAS Institute. 1985. SAS user's guide: Statistics. Version 5 ed. SAS Inst., Cary, NC.
Schindler, D.W. 1977. The evolution of phosphorus limitation in lakes. Science 195:260–262.
Shreve, B.R., P.A. Moore, Jr., T.C. Daniel, and D.R. Edwards. 1995. Reduction of phosphorus in runoff from field-applied poultry litter using chemical amendments. J. Environ. Qual. 24:106–111.
Sonzogni, W.C., S.C. Chapra, D.E. Armstrong, and T.J. Logan. 1982. Bioavailability of phosphorus inputs to lakes. J. Environ. Qual. 11:555–563.
Ueki, A., K. Matsuda, and C. Ohtsuki. 1986. Sulfate-reduction in anaerobic digestion of animal waste. J. Gen. Appl. Microbiol. 32:111–123.

Tillage and Nutrient Source Effects on Surface and Subsurface Water Quality at Corn Planting

Suling L. Zhao, Satish C. Gupta,* David R. Huggins, and John F. Moncrief

ABSTRACT

This study quantified the effects of tillage (moldboard plowing [MP], ridge tillage [RT]) and nutrient source (manure and commercial fertilizer [urea and triple superphosphate]) on sediment, NH_4+–N, NO^-_3–N, total P, particulate P, and soluble P losses in surface runoff and subsurface tile drainage from a clay loam soil. Treatment effects were evaluated using simulated rainfall immediately after corn (*Zea mays* L.) planting, the most vulnerable period for soil erosion and water quality degradation. Sediment, total P, soluble P, and NH^+_4–N losses mainly occurred in surface runoff. The NO^-_3–N losses primarily occurred in subsurface tile drainage. In combined (surface and subsurface) flow, the MP treatment resulted in nearly two times greater sediment loss than RT ($P < 0.01$). Ridge tillage with urea lost at least 11 times more NH^+_4–N than any other treatment ($P < 0.01$). Ridge tillage with manure also had the most total and soluble P losses of all treatments ($P < 0.01$). If all water quality parameters were equally important, then moldboard plow with manure would result in least water quality degradation of the combined flow followed by moldboard plow with urea or ridge tillage with urea (equivalent losses) and ridge tillage with manure. Tillage systems that do not incorporate surface residue and amendments appear to be more vulnerable to soluble nutrient losses mainly in surface runoff but also in subsurface drainage (due to macropore flow). Tillage systems that thoroughly mix residue and amendments in surface soil appear to be more prone to sediment and sediment-associated nutrient (particulate P) losses via surface runoff.

The combination of intensive cultivation and the presence of surface and subsurface drainage in southern Minnesota has been implicated in water quality degradation of the Minnesota River, the upper Mississippi River, and the Gulf of Mexico (Payne, 1994; Goolsby et al., 1999). Many soils in the North Central states, including those in southern Minnesota, have low hydraulic conductivity and thus limited drainage capacity (Wheaton, 1977). As a result, artificial drainage is a necessity for profitable crop production in this region. Even when subsurface drainage is enhanced in these soils, problems associated with poor drainage are still not satisfactorily resolved. This is because the landscape is relatively flat (<2% slope) and has many small depressions (pot holes) where water stands after snowmelt and heavy rainfall. Standing water hinders the timeliness of farm operations and is also deleterious to planted crops. To overcome these problems, farmers have installed surface tile inlets that drain water from these depressions to subsurface tile drains. These tile inlets allow transport of sediment and surface-applied chemicals to subsurface tiles, which ultimately flow to surface waters.

In addition to being wet, the soils in the upper Midwest are also cold during early spring, which delays corn planting, shortens the growing season, and thus reduces crop yield (Olsen and Schoeberl, 1970). To overcome problems associated with wet and cold soil conditions during early spring, farmers often moldboard plow in the fall to enhance soil drying and warming the following spring. One consequence of fall moldboard plowing, however, is the lack of surface residue cover during spring when soils are most vulnerable to detachment by spring rains.

Beef, hog, and dairy farming are also an important part of the economy in the area, and thus land application of manure is a common practice. Consequently, additional loading of nutrients and organic matter can occur both in surface runoff and in subsurface drainage. Possible methods to lower nutrient, herbicide, and organic matter loading of the Minnesota River include practices such as ridge tillage, which minimizes soil disturbance while preserving crop residues at the soil surface. Ridge tillage provides substantial residue cover from fall harvest to early spring when ridges are left undisturbed. At planting, surface cover is reduced in the planted row, but overall soil disturbance is minimal. Reestablishment of ridges in late June results in shallow mixing of surface soil, while maintaining cover. Surface residue cover in ridge tillage reduces soil erosion while the raised beds enhance soil warming in early spring (Gupta et al., 1990). One unknown consequence of ridge tillage is the effect of limited soil incorporation of

Suling L. Zhao, Resource 21, 7257 S. Tucson Way, Suite 200, Englewood, CO 80112. Satish C. Gupta and John F. Moncrief, Dep. of Soil Water, and Climate, 1991 Upper Buford Circle, Univ. of Minnesota, St. Paul, MN 55108. David R. Huggins, USDA-ARS, Dep. of Crop and Soil Sciences, Washington State Univ., Pullman, WA 99164. Received 17 May 2000. *Corresponding author (sgupta@soils.umn.edu).

Published in J. Environ. Qual. 30:998–1008 (2001).

Abbreviations: FWMC, flow-weighted mean concentration; MP, moldboard plow; M, manure; RT, ridge till; U, urea.

amendments such as fertilizer and manure on nutrient losses in artificial drainage systems.

Extensive literature exists on the effects of tillage, and to some extent, on the effects of manure alone or in combination with different tillage treatments on surface runoff and its quality (Young and Mutchler, 1976; Klausner et al., 1976; Young and Holt, 1977; Wendt and Corey, 1980; Mueller et al., 1984a,b; Converse et al., 1976; Ginting et al., 1998a,b; Hansen et al., 2000). However, most of these studies have been done on steep lands with moldboard and chisel plow systems. There is very limited information on relatively flat (0–2% slope) lands such as those found in the Minnesota River Basin with ridge tillage systems. Furthermore, there was no provision for subsurface drainage in most of these studies. Extensive literature (Gast et al., 1978; Baker and Johnson, 1981; Kanwar et al., 1988; Kladivko et al., 1991; Logan et al., 1993; Randall and Iragavarapu, 1995) also exists on commercial fertilizer effect on subsurface water quality but there is limited data (Randall et al., 2000) on manure effect either alone or in comparison with commercial fertilizer on subsurface water quality. Excellent review articles dealing with surface and subsurface water quality have also been reported (Logan et al., 1980; Fausey et al., 1995; Sharpley et al., 1998; Sims et al., 1998).

The goal of this study was to evaluate tillage and nutrient source interactions on sediment, nitrogen, and phosphorus losses from poorly drained, gently sloping land both in percolate solution via subsurface tile drains and in surface runoff via surface tile inlets. Specific objectives of this experiment were to evaluate the effects of (i) moldboard plowing versus ridge tillage and (ii) solid beef manure versus commercial fertilizer (urea and triple superphosphate) on soil and nutrient losses via surface runoff and subsurface drainage from a major soil in the Minnesota River Basin. The study was conducted immediately after corn planting, when soils were most vulnerable to soil erosion and surface runoff.

MATERIALS AND METHODS

The drainage plots were established in 1994 on Webster clay loam (fine-loamy, mixed, mesic Typic Haplaquoll), a common soil series in the Minnesota River Basin, at the Southwest Research and Outreach Center at Lamberton, MN. The details of the experimental setup, plot layout, and cultural practices are given in Zhao (1998). Briefly, the plots were 9.9 m wide and 18.2 m long (Fig. 1). Each plot was isolated to a depth of 1.8 m by trenching around plot borders and installing a 0.3-mm plastic sheet. Two perforated plastic tile drains, 10 cm in diameter, were installed at 1 m depth and 1.5 m away from the plot boundaries along its width. The tile drain away from the surface inlet was shut whereas the tile drain near the surface inlet was open during the course of this study. This arrangement drained a 16.7-m (18.2 m minus 1.5 m) length of the plot, one-half of a side of the tile drains, which may be 33.4 m apart. In other words, the plot setup simulated a tile drain spacing of 33.4 m. Tile drains were then connected to nonperforated PVC pipe, which emptied into a monitoring well. Surface inlets were located at the lowest point in the plots and drained surface runoff into the monitoring well.

The experiment was a randomized split-plot design with four replications. Main plots consisted of two tillage treat-

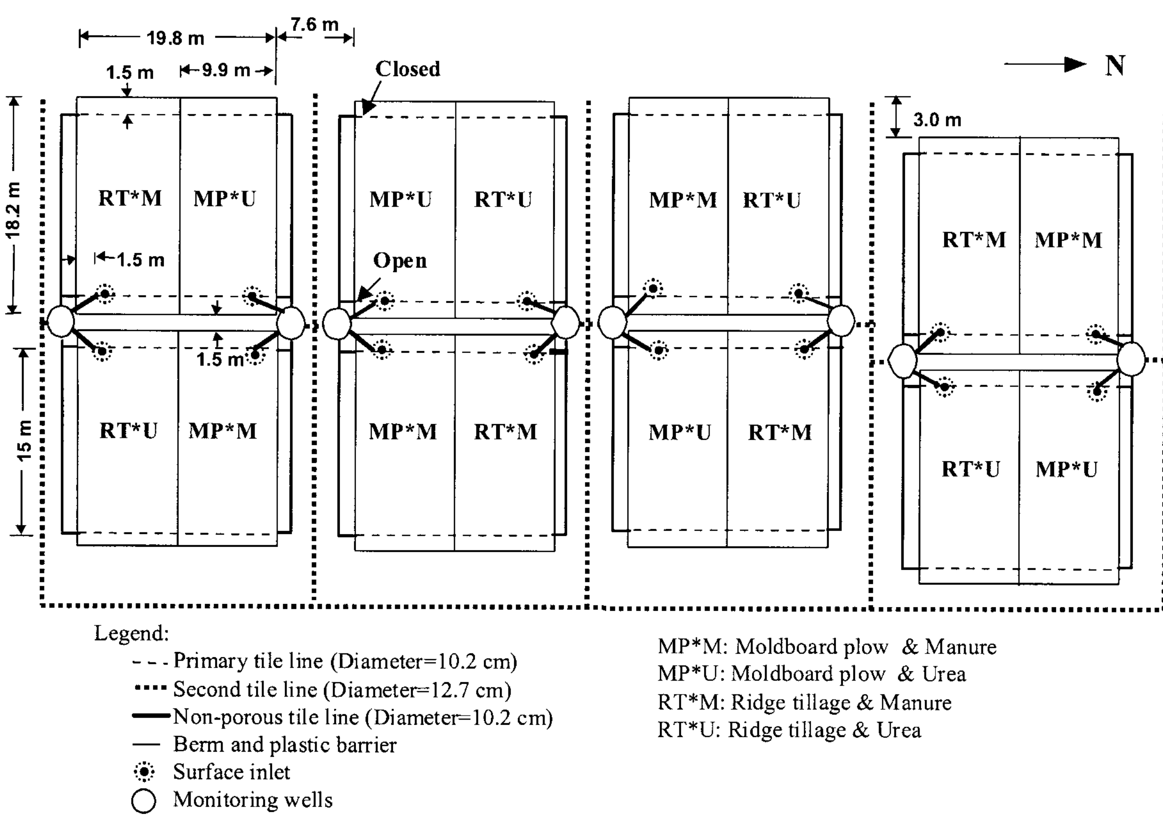

Fig. 1. Plot layout of the experiment on tillage and nutrient source effect on water quality of surface runoff and subsurface tile flow at the Southwest Research and Outreach Center, Lamberton, MN.

Table 1. Effect of tillage and nutrient source on surface inlet and subsurface tile flow characteristics following simulated rainfall on a Webster clay loam soil on 25–29 Apr. 1997.

Treatments	Antecedent soil moisture 0–60 cm depth	Rainfall depth	Rainfall intensity	Surface runoff: Starting time†	Surface runoff: Amount	Surface runoff: Percent of combined	Surface runoff: Percent of simulated rainfall	Subsurface tile drainage: Starting time†	Subsurface tile drainage: Amount	Subsurface tile drainage: Percent of combined	Subsurface tile drainage: Percent of simulated rainfall	Combined flow: Amount	Combined flow: Percent of simulated rainfall
	kg kg^{-1}	mm	mm h^{-1}	min	mm	%	%	min	mm	%	%	mm	%
Moldboard plow													
Manure	0.267	80.8	70.3	28.2	21.0	63.6	26.4	63.0	11.0	33.3	13.2	33.0	39.5
Urea	0.259	69.5	63.5	27.5	24.0	61.5	34.7	82.1	15.0	38.5	22.0	39.0	56.7
Ridge till													
Manure	0.271	83.5	66.5	24.0	25.0	54.3	30.4	38.5	21.0	45.7	25.4	46.0	55.8
Urea	0.259	79.8	70.8	24.3	25.0	56.8	33.3	25.6	19.0	43.2	23.5	44.0	56.8
Statistics													
Tillage	NS‡	NS	NS	NS	NS		NS	*	NS		NS	NS	NS
Nutrient source	NS	NS	NS	NS	NS		NS	NS	NS		NS	NS	NS
TNS§	NS	NS	NS	NS	NS		NS	NS	NS		NS	NS	NS

* Significant at the 0.10 probability level.
† Time interval between initiation of simulated rainfall and start of surface runoff or subsurface tile flow.
‡ Not significantly different.
§ Tillage by nutrient source.

ments: (i) fall moldboard plowing (MP) followed by two passes of field cultivation before corn planting and (ii) ridge tillage (RT), with ridges running parallel to the slope. Subplots were two annually applied nutrient management treatments: fall-applied solid beef manure containing straw bedding (M) versus spring-applied urea (U). The first application of manure was broadcast in fall 1994 and the first application of urea was in spring 1995. For the MP treatment, manure was incorporated right away into soil to about 20 cm depth with moldboard plowing. For the RT treatment, manure remained at the soil surface until ridges were reestablished in late June. Similarly, urea was surface-broadcast each spring just before corn planting. In the case of the MP treatment, urea was incorporated into the soil to about 5 cm depth with two passes of field cultivation. For the ridge tillage treatment, there was no incorporation of urea into the soil until late June, when ridges were rebuilt. There was slight mixing of manure and urea with surface soil when ridges were rebuilt in late June in the RT treatment.

Application rates of manure and urea were based on yield goal and the University of Minnesota recommendations (Rehm et al., 1993). Estimated available N for fall manure application was 107, 157, and 157 kg N ha^{-1} in 1994, 1995, and 1996 (10.5, 17.0, and 22.1 Mg ha^{-1} of oven-dry beef manure), respectively. Amount of manure applied was based on mineral N and total N analysis. It was assumed that all mineral N (NH_4^+–N and NO_3^-–N) and 30% of the organic N in manure was available to corn in the first year (Sutton et al., 1986). Over the 3-yr period, mineral N and total N concentrations of the manure varied from 0.11 to 0.26% and 2.04 to 2.5%, respectively. Phosphorus application due to manure addition equaled 121, 158, and 196 kg P_2O_5 ha^{-1} in 1994, 1995, and 1996, respectively.

Spring urea applications in 1995, 1996, and 1997 were 107, 157, and 157 kg N ha^{-1}, respectively. In 1995, a one-time application of triple superphosphate at the rate of 121 kg P_2O_5 ha^{-1} was also surface-applied to all urea plots. This application rate was based on soil test P levels and the University of Minnesota recommendations (Rehm et al., 1993). In case of the MP treatment, triple superphosphate was incorporated into the soil to about 5 cm depth during two passes of field cultivation. In the case of the RT treatment, triple superphosphate remained at the soil surface until ridges were rebuilt in late June 1995. In addition to the above manure and fertilizer application rates, a small but equal amount of starter fertilizer was also applied to all plots at planting. Corn was grown each year starting in 1995.

All 16 experimental plots were subjected to simulated corn planting (no corn seed) on 22 Apr. 1997. Starting on 25 April, a 4.9- by 11-m area around the surface inlet in each plot was subjected to simulated rainfall using the rainfall simulator of Hermsmeier et al. (1963). Simulated rainfall was carried out on one plot at a time and therefore it took 5 d to complete the rainfall simulation on all 16 plots. Length of the rain-impacted area coincided with the length of the plot. Before simulated rainfall, soil samples were taken to a depth of 60 cm for antecedent moisture content. Similarly, crop residue cover measurements were also made before rainfall simulation using the line-transect method of Laflen et al. (1981). The residue cover measurements were taken along two diagonal transects in each plot.

Rainfall was applied at an average intensity of 68 mm h^{-1}. The rainfall amount applied to each individual plot varied from 67 to 93 mm, but these differences were not statistically significant (Table 1). Rainfall application averaged over all plots equaled 78 mm, which is an equivalent to rainfall application for 1 h and 10 min. According to the Depth–Duration–Frequency (DDF) curves for the state of Minnesota, natural rainfall amounts for 1-h storm events that occur every 10, 25, and 100 yr are 52, 58, and 72 mm, respectively. Therefore, simulated rainfall intensity of 68 mm h^{-1} corresponds to a 1-hour-75-year natural rainstorm.

Both surface runoff and subsurface tile drainage were measured by tipping bucket devices that were connected to CR-10 data loggers (Campbell Scientific,[1] Logan, UT). Volume-distributed (composite water sample over a certain number of tips) runoff samples from surface inlets were taken by automated samplers. Time-distributed (composite water sample over a certain time interval) subsurface drainage samples were collected manually. The other details of sampling setup and protocol are given in Zhao (1998).

Water samples from both surface runoff and subsurface tile drainage were analyzed for sediment, NO_3^-–N, NH_4^+–N, total P, and soluble P (dissolved molybdate reactive P). Sediments were measured by evaporating 200 mL of water suspension at 105°C. Nitrate N and NH_4^+–N were analyzed using the

[1] The company name is provided for the benefit of the reader and is not an endorsement by the University of Minnesota or the USDA-ARS.

conductimetric method of Carlson (1978, 1986). Total P in water suspension was determined by perchloric–nitric acid digestion as described in USEPA standard procedure (USEPA, 1981). Soluble P was measured using the blue molybdate method of Wendt and Corey (1980). Since the water used for simulated rainfall (city water from a local municipal hydrant) contained a high concentration of dissolved salts, gravimetric measurements of sediment in water samples from both surface runoff and subsurface tile drainage were corrected for soluble salts. There was no detectable N and P in the water used for simulated rainfall. Total sediment and nutrient losses from each plot were calculated by multiplying the individual sample concentrations with flow volume and then summing the amounts over the entire period of the simulation.

Analysis of variance (ANOVA) of tillage, nutrient source treatments, or their interactions was performed using SAS (SAS Institute, 1994). The parameters tested were: time to surface runoff via surface inlet, time to percolation via subsurface tile drain, volume of surface runoff, volume of percolate, and the amounts of sediment, NO_3^-–N, NH_4^+–N, total N, total P, and soluble P losses in surface runoff, in subsurface tile drainage and the combined flow (surface runoff plus subsurface tile drainage). Since there was a significant tillage by nutrient source interaction on NH_4^+–N, NO_3^-–N, total P, and soluble P losses, a pair-wise mean comparison was also performed on these parameters using the method described by Gomez and Gomez (1984, p. 199–204).

RESULTS AND DISCUSSION

There was no statistical difference in antecedent soil moisture content, amount of rainfall applied, and rainfall intensity between various treatments (Table 1). This lack of statistical difference in initial soil conditions and rainfall characteristics made it possible to compare losses from various tillage and nutrient source treatments.

Water Losses

Surface Runoff

Tillage and nutrient source had no significant effect on time to surface runoff via surface inlets, total runoff, or runoff as a percentage of simulated rainfall (Table 1). This lack of tillage and nutrient source effect on surface runoff appears to be due to the lack of differences in surface storage between treatments after secondary tillage and corn planting. Since the ridges were parallel to the direction of slope, there was very little surface storage in the RT treatment. In the MP treatment, two passes of field cultivation in early spring obliterated any surface storage that was present after fall moldboard plowing.

Subsurface Tile Drainage

Moldboard plowing significantly delayed (by 40 min) the start of tile flow compared with RT, while there was no significant difference in the start of tile flow between the manure and urea treatments (Table 1). Early tile flow in the RT treatment appears to be associated with preferential flow, as evidenced by the presence of sediment and NH_4^+–N in subsurface tile drainage (discussed later). Tillage had a significant effect on peak flow rates. The peak tile flow rates (Fig. 2) were much greater from the RT (RT*M and RT*U) than the MP (MP*M and MP*U) treatments, again suggesting preferential flow in RT compared with the MP treatment. Average peak tile flow rates were 0.64, 0.41, 0.17, and 0.15 cm h^{-1} for RT*U, RT*M, MP*M, and MP*U, respectively. There was no significant effect of tillage on cumulative tile drainage, thus suggesting nearly equal surface and subsurface storage in the MP and the RT treatments.

Manure application had no significant effect on the start of subsurface tile flow or on total tile drainage (Table 1). The lack of a manure effect on tile flow is possibly due to short duration (3 yr) of manure applications and thus an absence of any significant improvement in soil structure. It is possible that additional years of manure application will lead to significant improvement in soil structure, including macropore development (Munyankusi et al., 1994; Edwards and Lofty, 1982). Another possible reason is the high clay content (29.4%) of the study soil. Clay soils tend to show the least improvement in physical conditions from manure application (Mbagwu, 1989).

Combined Flow

Tillage and nutrient source had no significant effect on combined (surface runoff plus subsurface tile drainage) water losses (Table 1). Surface runoff was the dominant fraction of the total water losses through artificial drainage. Total water losses as a percentage of simulated rainfall varied from 40% for MP*M to 57% for the RT*U treatment. This shows that surface inlets along with subsurface tiles drain a large volume of water from landscapes in southwestern Minnesota during early spring. This large drainage is desirable for timely crop planting and healthy early crop growth, especially in the fine-textured soils of the region.

Sediment Losses

Surface Runoff

Sediment losses from the MP plots were nearly two times higher than losses from the RT plots (Table 2). Since tillage had no significant effect on surface runoff losses, the increase in sediment losses was mainly due to greater sediment concentration in surface runoff water from the MP compared with the RT treatment. Flow-weighted mean sediment concentration for the MP treatment (3.2 g L^{-1}) was two times more than the concentration from the RT treatment (1.4 g L^{-1}). The higher sediment concentration from the MP plots was due to two major factors: (i) lack of residue cover and (ii) increased surface disturbance. The surface residue cover in the MP plots was 12% compared with 45% in the RT plots. Beside the decrease in soil detachment, higher residue cover between the rows in the RT treatment also decreased the rate of overland flow, reducing its erosive power and trapping sediment from the runoff. After two passes of field cultivation and corn planting, surface soil in the MP treatment was disturbed and had many loose and unconsolidated aggregates (visual observations) that were vulnerable to rainfall detach-

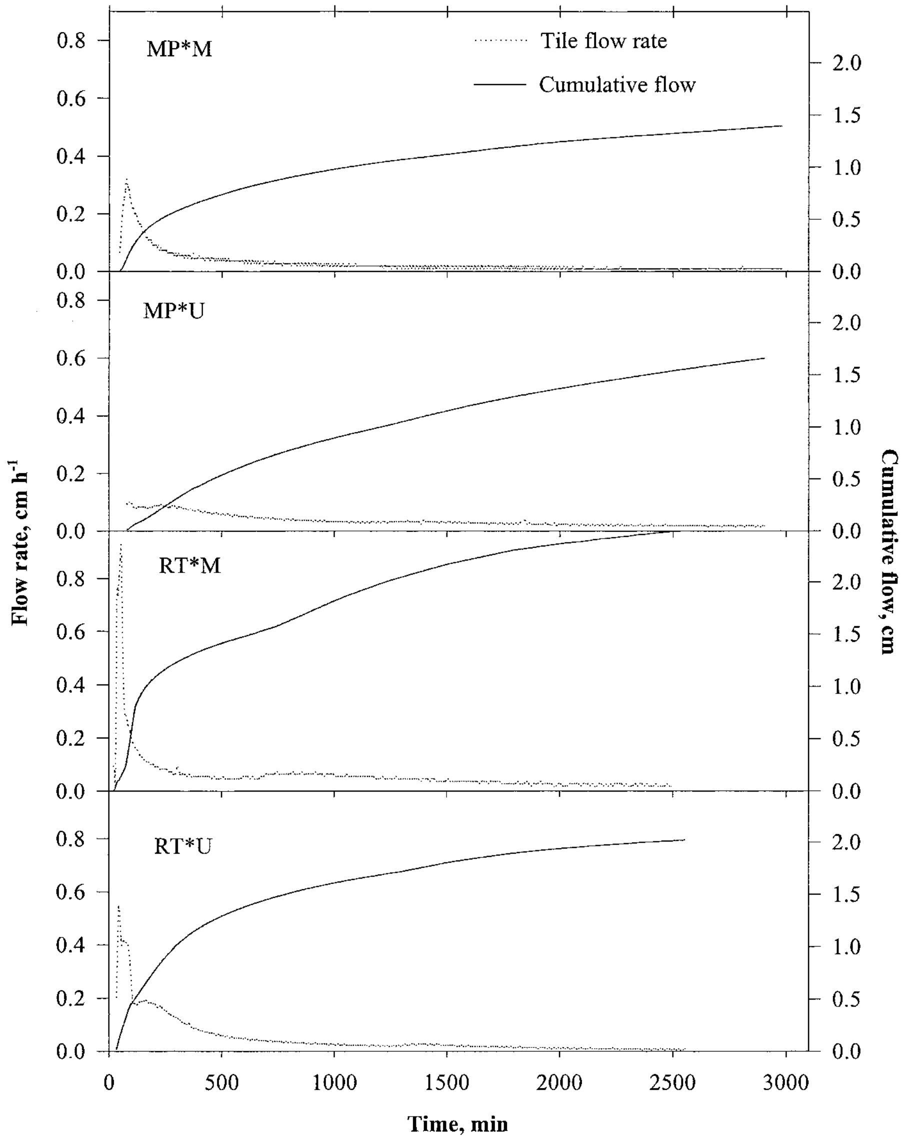

Fig. 2. An example of the variation in cumulative flow and flow rate through tile lines as a function of time for moldboard plow with manure (MP*M), moldboard plow with urea (MP*U), ridge tillage with manure (RT*M), and ridge tillage with urea (RT*U) treatments on a Webster clay loam soil.

ment and transport. Comparatively, the RT treatment had minimal soil disturbance and few loose or unconsolidated soil aggregates present at the time of simulated rainfall.

Manure application had no significant effect on sediment losses compared with the urea treatment (Table 2). This is consistent with the manure effects on water losses in surface runoff, again suggesting that 3 yr of manure application did not significantly improve soil stability or infiltration characteristics (Mbagwu, 1989). There was no tillage by nutrient source interaction on sediment losses in surface runoff (Table 2).

Subsurface Tile Drainage

Contrary to trends in sediment loss in surface runoff, sediment loss through subsurface tile drainage was significantly greater (about five times) from the RT than the MP treatment (Table 2). This increase in sediment loss from the RT treatment was mainly due to preferential flow of water. About 75% of the tile flow samples from the RT treatment had a detectable level of sediment compared with only about 40% of the samples from the MP plots. Subsurface tile flow sediment mostly appeared early in the hydrograph, near the peak flow rate (Fig. 2 and 3). Sediment concentration in subsurface tile drainage from the RT plots was as high as 0.4 g L^{-1} compared with 0.1 g L^{-1} from the MP plots. Several hours after the simulated rainfall stopped, sediment in subsurface tile drainage was nondetectable. We hypothesize that the preferential flow in the RT treatment was due to the presence of large continuous pores (macropores) that were not disturbed since harvest the previous fall. These macropores carried some of the runoff and associated sediment to subsurface tile drains. The observation of preferential flow in tile-drained soils has

Table 2. Effect of tillage and nutrient source on sediment losses through surface inlets and subsurface tile drains after 78 mm of simulated rainfall on a Webster clay loam soil on 25–29 Apr. 1997.

Treatments	Sediment loss: Surface runoff		Subsurface tile		Combined flow	
	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	FWMC† g L^{-1}
Moldboard plow						
Manure	609	98.6	9	1.4	618	1.87
Urea	846	98.2	16	1.8	862	2.21
Ridge till						
Manure	342	87.5	49	12.5	391	0.85
Urea	344	82.4	73	17.6	417	0.95
Statistics						
Tillage	***		**		***	
Nutrient source	NS‡		NS		NS	
Tillage by nutrient sources	NS		NS		NS	

** Significant at the 0.05 probability level.
*** Significant at the 0.01 probability level.
† Flow-weighted mean concentration.
‡ Not significantly different.

also been reported by Evert et al. (1989). These authors observed the presence of adsorbed tracers, Li^+ and Rhodamine WT, reaching the tile line within 25 min after the tracers were applied with irrigation. Also in their study, the timing of peak flow for both adsorbed and nonadsorbed tracers occurred at about the same time after the start of the irrigation. It is also possible that some of the sediment in subsurface tile drainage in our study may have been due to erosion of macropore channels.

Manure application had no effect on sediment losses in subsurface tile drainage. There was also no tillage by nutrient source interaction on subsurface tile drainage sediment losses.

Combined Flow

Most of the sediment losses occurred in surface runoff, varying from 82% for the RT*U treatment to 99% for the MP*M treatment (Table 2). The sediment losses in subsurface tile drainage were as high as 18% of the total sediment losses (RT*U). This identifies preferential flow as an important pathway for sediment loss in the RT treatment.

Tillage treatments had a significant effect on combined sediment losses. Moldboard plowing produced 740 kg ha^{-1} of sediment compared with 404 kg ha^{-1} for the RT treatment, a decrease of 45%. Flow-weighted mean concentration (FWMC) for sediment from the MP treatment were >2 g L^{-1} in comparison with about 0.9 g L^{-1} for the RT treatment (Table 2).

As with the surface runoff and subsurface tile drainage, manure application had no significant effect on sediment loss in combined flow compared with the urea treatment. There was also no tillage by nutrient source interaction on sediment losses in combined flow.

Nitrogen Losses

Surface Runoff

There was a strong tillage by nutrient source interaction on NH_4^+–N and NO_3^-–N losses in surface runoff (Table 3). The RT*U treatment lost more NH_4^+–N than any other treatment. This was mainly due to a lack of urea mixing into the soil. On the other hand, the RT*M treatment lost more NO_3^-–N than the RT*U, MP*U, and MP*M treatments. Lower losses of NH_4^+–N or NO_3^-–N with moldboard plowing shows that mixing of applied fertilizer by tillage, whether manure or urea, was helpful in reducing mineral N (NH_4^+–N and NO_3^-–N)

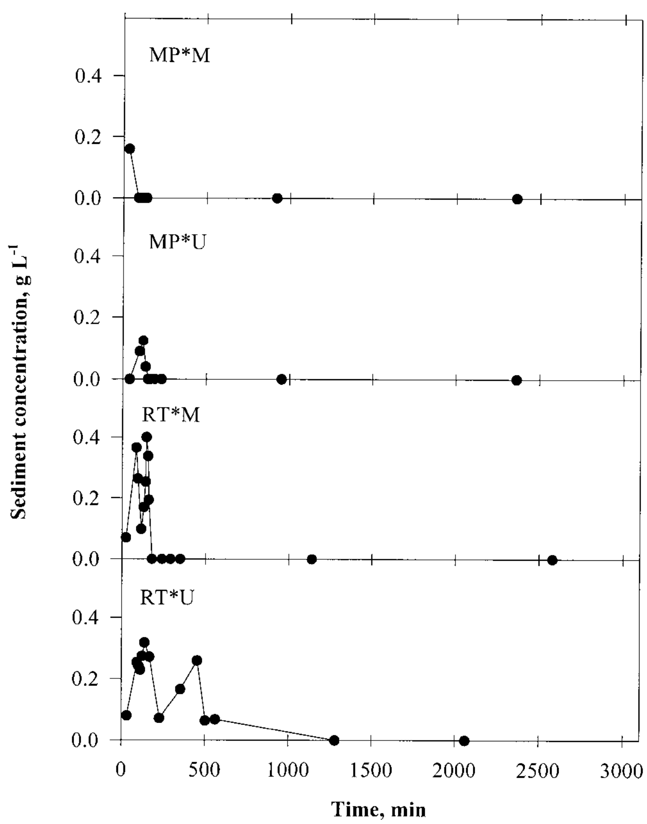

Fig. 3. An example of the variation in sediment concentration in tile line flow as a function of time for moldboard plow with manure (MP*M), moldboard plow with urea (MP*U), ridge tillage with manure (RT*M), and ridge tillage with urea (RT*U) treatments on a Webster clay loam soil.

Table 3. Effect of tillage and nutrient source on NH_4^+–N and NO_3^-–N losses through surface inlet and subsurface tile after 78 mm of simulated rainfall on a Webster clay loam soil on 25–29 Apr. 1997.

	Surface runoff				Subsurface tile drainage				Combined flow			
	NH_4^+–N		NO_3^-–N		NH_4^+–N		NO_3^-–N		NH_4^+–N		NO_3^-–N	
Treatments	Loss	% combined	Loss	% combined	Loss	% combined	Loss	% combined	Loss	FWMC†	Loss	FWMC
	g ha^{-1}	%	g ha^{-1}	%	g ha^{-1}	%	g ha^{-1}	%	g ha^{-1}	mg L^{-1}	g ha^{-1}	mg L^{-1}
Moldboard plow												
Manure	39.2b‡	99.0	35.4c	13.4	0.4	1.1	229.0	86.6	39.6b	0.12	264.4b	0.8
Urea	152.3b	73.1	75.9bc	15.7	55.9	26.8	408.8	84.4	208.2b	0.53	484.6b	1.24
Ridge till												
Manure	240.3b	81.2	254.9a	28.5	55.5	18.8	638.1	71.5	295.8b	0.64	893.0a	1.94
Urea	2750.0a	84.2	128.8b	25.2	514.6	15.8	382.4	74.8	3264.7a	7.42	511.2ab	1.16
Statistics												
Tillage	***		***		*		NS§		***		**	
Nutrient source	**		*		*		NS		***		NS	
Tillage by nutrient source	**		***		NS		NS		***		**	

* Significant at the 0.10 probability level.
** Significant at the 0.05 probability level.
*** Significant at the 0.01 probability level.
† Flow-weighted mean concentration.
‡ Means in a column with the same letter are not significantly different.
§ Not significantly different.

losses in surface runoff. For the ridge tillage treatment, manure application significantly reduced NH_4^+–N losses compared with the urea treatment, mainly due to slow release of N from applied manure.

Ammonium N concentrations in surface runoff were generally less than 10 mg L^{-1} (data not shown). Occasionally, NH_4^+–N concentration from the RT*U treatment was as high as 30 mg L^{-1}. Nitrate N concentrations in surface runoff were almost always <1 mg L^{-1}. This value is much less than the 10 mg L^{-1} drinking water standard of the USEPA (2000).

Subsurface Tile Drainage

Tillage had a significant effect on NH_4^+–N losses via subsurface tile drainage (Table 3). Ridge tillage resulted in 10 times more NH_4^+–N losses than the moldboard plow treatment, mainly due to poor soil mixing of urea and manure, which in turn, allowed a large amount of dissolved NH_4^+–N in surface water to percolate through the macropores into tile drains. This explanation is consistent with our earlier observations of preferential flow and greater NH_4^+–N losses in surface runoff from the RT compared with the MP treatments.

The spring-applied urea treatment resulted in 10 times higher NH_4^+–N leaching losses than the fall-applied manure treatment. The reduction in NH_4^+–N losses from the manure treatment was mainly due to slow release of NH_4^+–N from the organic fraction of the manure compared with very rapid conversion of urea to NH_4^+–N in the urea plots. Urea hydrolysis depends upon several soil factors including temperature, water content, texture, organic matter content, and depth. For unsaturated flow conditions, the urea hydrolysis rate constant for first-order rate reaction has been shown to vary from 0.016 h^{-1} (Wagenet et al., 1977) to 0.25 h^{-1} (Ardakani et al., 1975). These rate constants translate to 11.9 and 2.7 h for 95% of the urea to hydrolyze. Our rainfall simulations did not start for at least 3 d after the application of urea, allowing plenty of time for it to hydrolyze.

Contrary to NH_4^+–N losses, there was no effect of either tillage or nutrient source treatments on NO_3^-–N losses via subsurface tile drainage.

Ammonium cations have difficulty passing through soil without being retained by negatively charged organic matter and clay minerals. The appearance of NH_4^+–N in subsurface flow suggests that the percolating water had little reaction with the soil matrix and was preferentially transported to subsurface tile drains. Since the continuity of preferential pathways (earthworm macropores, cracks) to the soil surface is highly influenced by tillage practices, a significant difference in NH_4^+–N concentration between the tillage treatments would be expected. On the other hand, NO_3^-–N anions are easily leached through the soil matrix. This means NO_3^-–N movement will be controlled by the soil profile characteristics as well as soil surface conditions. These differences in NH_4^+–N and NO_3^-–N flow characteristics are illustrated in Fig. 4. Presence of NH_4^+–N in subsurface tile drainage only occurred at the peak flow period, thus suggesting the occurrence of preferential flow. In contrast, NO_3^-–N was present both during the preferential and matrix flow periods, although its concentration during matrix flow was relatively constant, thus suggesting a continuous leaching of NO_3^-–N from the soil profile.

Ammonium N in subsurface tile drainage mostly occurred during early flow and its concentrations were typically around 2 to 3 mg L^{-1} (Fig. 4). Nitrate N concentrations in subsurface tile drainage were mostly in the range of 3 to 5 mg L^{-1}. The subsurface drainage NO_3^-–N concentrations are much lower compared with other studies (Gast et al., 1978; Logan et al., 1993; Randall and Iragavarapu, 1995; Fausey et al., 1995). This is partially because our research site had not received any fertilizer addition for more than 35 yr prior to initiation

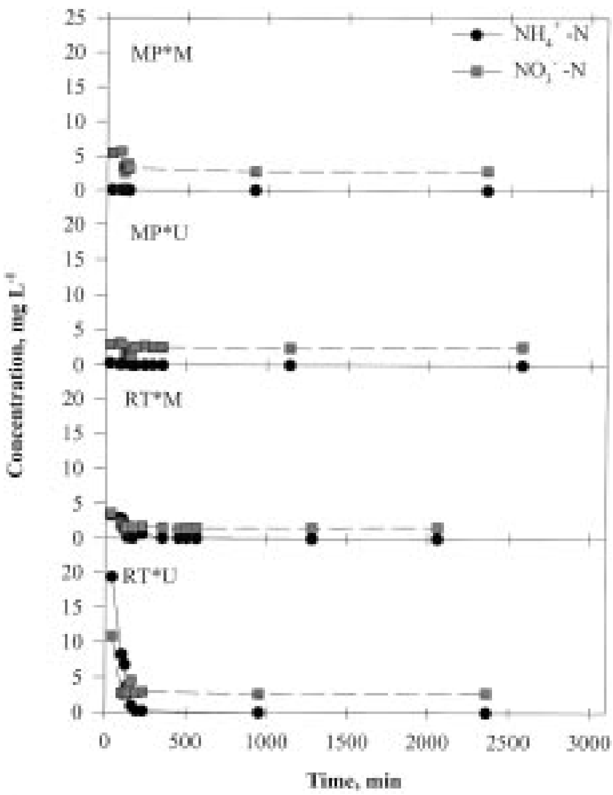

Fig. 4. An example of the variation in NH_4^+–N and NO_3^-–N concentration in tile line flow as a function of time for moldboard plow with manure (MP*M), moldboard plow with urea (MP*U), ridge tillage with manure (RT*M), and ridge tillage with urea (RT*U) treatments on a Webster clay loam soil.

of this study in 1994 and was thus initially low in residual mineral N and soil test P levels.

Combined Flow

There were significant tillage by nutrient source interactions on both NH_4^+–N and NO_3^-–N losses in combined (surface runoff and subsurface tile drainage) water flow (Table 3). The RT*U treatment lost at least 11 times more NH_4^+–N than any other treatment whereas the RT*M treatment lost at least 75% more NO_3^-–N than any other treatment. The main reason for interactions of tillage with nutrient source on NH_4^+–N and NO_3^-–N losses in combined flow is because most of the NH_4^+–N losses occurred in surface runoff and there was a significant tillage–nutrient source interaction on NH_4^+–N losses in surface runoff. Although there was no tillage and nutrient source interaction on NO_3^-–N losses through subsurface tile drainage, the highly significant interaction for NO_3^-–N losses in surface runoff caused a significant interaction for NO_3^-–N losses in combined flow. More than 72% of the NO_3^-–N losses occurred via tile drainage, whereas more than 73% of the NH_4^+–N losses occurred via surface runoff.

Flow-weighted mean concentrations (FWMC) of NH_4^+–N in combined flow were 0.12, 0.53, 0.64, and 7.42 mg L^{-1} for MP*M, MP*U, RT*M, and RT*U treatments, respectively (Table 3). Except for the MP*M treatment, these high concentrations from the other three treatments have the potential to cause harm to humans, whereas the high concentration from the RT*U treatment has the potential to cause harm to both humans and fish (Sharpley et al., 1998). Flow-weighted mean concentrations of NO_3^-–N were all <2 mg L^{-1}, which is below the 10 mg L^{-1} water standards of the USEPA (2000).

Phosphorus Losses

Surface Runoff

There was a significant tillage by nutrient source interaction on both total P and soluble P losses in surface runoff (Table 4). Total P losses were greatest from the RT*M treatment followed by the MP*U, MP*M, and RT*U treatments. These treatment rankings are different from the sediment loss rankings because of the differences in soluble P contributions from surface manure and crop residues. Soluble P losses from the RT*M treatment were at least three times more than any other treatment. For the RT*M treatment, 64% of the total P was in the form of soluble P. However, for the MP*U treatment, 91% of the total P was in the form of sediment-associated particulate P. These data suggest that when manure was not well mixed with the soil (RT*M), soluble P from manure as well as from crop residues accounted for most of the total P losses in surface runoff. On the other hand, treatments such as MP*U, which produced the greatest amount of sediment and sediment-bound phosphorus (particulate P), accounted for most of the total P losses. These results suggest that surface-applied manure and crop residue are significant sources of soluble P losses, especially from a water quality perspective. Furthermore, tillage practices that mix manure and crop residue into the soil would significantly reduce soluble P losses. These observations are similar to the findings of Ginting et al. (1998b).

Subsurface Tile Drainage

Both tillage and nutrient source had a significant effect on total P losses via subsurface tile drainage (Table 4). Ridge tillage had 26 times higher total P losses than the moldboard treatment, mainly due to preferential flow of surface runoff that carried soluble P from surface-applied manure and crop residues. Application of manure resulted in four times higher total P losses in subsurface tile drainage, again mainly due to preferential flow of surface runoff, which contained high concentrations of soluble P from manure. The presence of P in subsurface drainage has also been observed in several other studies such as sandy and high organic matter soils, and in soils where there has been overfertlization or excessive use of organic wastes (Sims et al., 1998).

Soluble P losses in subsurface tile drainage were significantly affected by tillage and nutrient source interactions (Table 4). The RT*M treatment resulted in at least 11 times more soluble P losses than any other treatment. This is consistent with the observation of highest soluble P losses in surface runoff from the RT*M treatment. The above discussion clearly shows that soil mixing of

Table 4. Effect of tillage and nutrient source on total P and soluble P (dissolved molybdate reactive P) losses through surface inlet and tile line after 78 mm of simulated rainfall on a Webster clay loam soil on 25–29 Apr. 1997.

	Surface runoff				Subsurface tile drainage				Combined flow			
	Total P		Soluble P		Total P		Soluble P		Total P		Soluble P	
Treatments	Loss	% combined	Loss	% combined	Loss	% combined	Loss	% combined	Loss	FWMC†	Loss	FWMC
	g ha^{-1}	%	g ha^{-1}	%	g ha^{-1}	%	g ha^{-1}	%	g ha^{-1}	mg L^{-1}	g ha^{-1}	mg L^{-1}
Moldboard plow												
Manure	508.4b‡	98.9	111.5b	96.0	5.7	1.1	4.6b	4.0	514.1b	1.56	116.1a	0.35
Urea	635.3a	99.6	54.7b	99.8	2.4	0.4	0.1b	0.2	637.7b	1.64	54.8a	0.14
Ridge till												
Manure	674.2a	79.2	432.9a	75.6	177.3	20.8	140.0a	24.4	851.5a	1.85	572.9b	1.25
Urea	289.0c	88.4	79.7b	87.1	37.8	11.6	11.8b	12.9	326.8c	0.74	91.5a	0.21
Statistics												
Tillage	*		***		**		**		NS§		***	
Nutrient source	**		***		*		**		***		***	
Tillage by nutrient source	***		***		NS		**		***		***	

* Significant at the 0.10 probability level.
** Significant at the 0.05 probability level.
*** Significant at the 0.01 probability level.
† Flow-weighted mean concentration.
‡ Means in a column with the same letter are not significantly different.
§ Not significantly different.

manure is helpful in reducing soluble P losses both in surface runoff and in subsurface tile drainage.

Combined Water Flow

Similar to total P losses in surface runoff, total P losses in combined flow were highest for the RT*M treatment, followed by the MP*U, MP*M, and RT*U treatments (Table 4). Total P losses in surface runoff accounted for about 79% (RT*M) to 100% (MP*U) of the total P losses in combined water flow.

Soluble P losses from the RT*M treatment were 573 g ha^{-1}, much greater than any other treatment (Table 4). Comparatively, soluble P losses from the MP*M treatment were 116 g ha^{-1} and not significantly different from the RT*U and the MP*U treatments. These data suggest that surface-applied manure in RT would result in significantly higher soluble P losses in combined flow. Of course, a majority of the soluble P losses are in surface runoff. Nevertheless, the treatments that enhance preferential flow (e.g., ridge tillage) could contribute as high as 21% of total P and 24% of soluble P losses in combined flow due to preferential flow pathways.

Flow-weighted mean concentrations of total P were 1.56, 1.64, 1.85, and 0.74 mg L^{-1} for MP*M, MP*U, RT*M, and RT*U, respectively. These values are much higher than 0.10 mg L^{-1}, the critical concentration for streams (USEPA, 1986). Flow-weighted mean concen-

Table 5. Relative rankings of water and associated pollutant losses after 78 mm of simulated rainfall on a Webster clay loam soil, April 1997.†

	Individual loss rankings							
	Water	Sediment	ND$_4^+$–N	NO_3^-–N	Total P	Soluble P	Combined impact	Combined impact minus water losses
Surface runoff								
Moldboard plow								
Manure	1	2	1	1	2	3	10	9
Urea	2	3	2	2	3	1	13	11
Ridge till								
Manure	3	1	3	4	4	4	19	16
Urea	3	1	4	3	1	2	14	11
Subsurface tile drainage								
Moldboard plow								
Manure	1	1	1	1	2	2	8	7
Urea	2	2	2	3	1	1	11	9
Ridge till								
Manure	4	3	2	4	4	4	21	17
Urea	3	4	3	2	3	3	18	15
Combined flow								
Moldboard plow								
Manure	1	3	1	1	2	3	11	10
Urea	3	4	2	2	3	1	15	12
Ridge till								
Manure	2	1	3	4	4	4	18	16
Urea	3	2	4	3	1	2	15	12

† 1 is the least effect (i.e., lowest total loss of pollutant), while 4 is the highest effect (i.e., greatest total loss of pollutant) in comparison with the other three treatments. If the losses are equal for two treatments, then the rankings are the same.

tration of soluble P was 0.35, 0.14, 1.25, and 0.21 mg L^{-1} for MP*M, MP*U, RT*M, and RT*U, respectively. Except for the RT*M treatment, the soluble P FWMCs for the other three treatments are below the proposed allowable limit of 1.0 mg L^{-1} for agricultural runoff (USEPA, 1986).

Overall Evaluation of Water Quality Effects

We characterized the overall effect of the four management treatments on water quality by ranking each treatment from 1 (least effect) to 4 (highest effect) for each of the six parameters (water, sediment, NH_4^+–N, NO_3^-–N, total P, and soluble P losses). This ranking was done for both surface and subsurface flow and for the combined flow. Rankings were similar for both losses and FWMC. Therefore, only the loss rankings are presented (Table 5). For each treatment, ranking scores for each loss parameter were summed for an overall score representing the combined effect of the treatment on water quality. This procedure assumes that all six parameters have an equal effect on water quality. Despite this oversimplification, the procedure is helpful in the qualitative ranking of the four treatments.

The results show that MP*M had the least overall effect followed by MP*U and RT*U (equivalent losses) and then RT*M on water quality of the combined flow. In the case of surface runoff and subsurface tile drainage water quality, the ranking was: MP*M (least) $<$ MP*U $<$ RT*U $<$ RT*M (most). This order of the rankings was the same when water losses were excluded from the combined effect (Table 5). Because of the lack of manure mixing and the presence of preferential flow, RT*M had the most negative water quality effect. On the other hand, complete mixing of manure with absence of preferential flow helped the MP*M treatment to have the least negative water quality effect.

CONCLUSIONS

In this study, surface runoff through surface tile inlets was the major conduit for transport of water, sediment, total P, soluble P, and NH_4^+–N losses from two tillage and two nutrient source treatments in early spring. Subsurface tile drainage, on the other hand, was the major pathway for transport of NO_3^-–N from these treatments. Tillage systems that disturb the soil surface to a great degree (e.g., MP) are susceptible to much higher sediment and sediment-associated nutrient (total P) losses. Thus, if off-site damage by sediment and sediment-associated nutrients is of concern then the use of tillage systems that minimize soil mixing is better than the tillage systems where there is thorough mixing of the surface soil. Ridge tillage resulted in greater losses of NO_3^-–N and soluble P than the moldboard plow treatments. If off-site damage from soluble nutrients such as nitrate and soluble P is of concern then tillage systems that mix manure and inorganic fertilizer into the soil are beneficial. The data reported in this paper are from one simulated rainfall event. If these trends continue on an annual basis, then these contrasting effects could pose a dilemma when considering high-residue tillage system alternatives for artificially drained soils. The dilemma is whether to minimize sediment-associated nutrient losses or soluble nutrient losses. This is especially important when manure is applied. If all water quality parameters were assumed equally important, then RT*M resulted in highest water quality degradation of the combined flow followed by RT*U and MP*U (equivalent losses) and MP*M.

ACKNOWLEDGMENTS

This research was partially supported with funds from the USDA Special Water Quality Grant, USDA/93-34214-8862. The authors thank Dr. Mike Lindstrom, USDA-ARS, Morris, MN for loaning the rainfall simulator and Mr. Gary Amunson of USDA-ARS, Morris, MN for setting up and running the siumlator. The authors also acknowledge the helpful comments of an anonymous reviewer.

REFERENCES

Ardakani, M.S., M.G. Volz, and A.D. McLaren. 1975. Consecutive steady state reactions of urea, ammonium, and nitrate nitrogen in soil. Can. J. Soil Sci. 55:83–91.

Baker, J.L., and H.P. Johnson. 1981. Nitrate-nitrogen in tile drainage as affected by fertilization. J. Environ. Qual. 10:519–522.

Carlson, R.M. 1978. Automated separation and conductimetric determination of ammonia and dissolved carbon dioxide. Anal. Chem. 50:1528–1531.

Carlson, R.M. 1986. Continuous flow reduction of nitrate to an ammonia with granular zinc. Anal. Chem. 58:1590–1591.

Converse, J.C., G.D. Bubenzer, and W.H. Paulson. 1976. Nutrient losses in surface runoff from winter spread manure. Trans. ASAE 19:517–519.

Edwards, C.A., and J.R. Lofty. 1982. Nitrogenous fertilizers and earthworm population in agricultural soils. Soil Biol. Biochem. 114: 515–521.

Evert, C.J., R.S. Kanwar, E.C. Alexander Jr., and S.C. Alexander. 1989. Comparison of tracer mobilities under laboratory and field conditions. J. Environ. Qual. 18:491–498.

Fausey, N.R., L.C. Brown, H.W. Belcher, and R.S. Kanwar. 1995. Drainage and water quality in Great Lakes and Corn Belt States. J. Irrig. Drain. Eng. 121:283–288.

Gast, R.G., W.W. Nelson, and G.W. Randall. 1978. Nitrate accumulation in soils and loss in tile drainage following nitrogen application to continuous corn. J. Environ. Qual. 7:258–262.

Ginting, D., J.F. Moncrief, S.C. Gupta, and S.D. Evans. 1998a. Corn yield, runoff, and sediment losses from manure and tillage systems. J. Environ. Qual. 27:1396–1402.

Ginting, D, J.F. Moncrief, S.C. Gupta, and S.D. Evans. 1998b. Interaction between manure and tillage system on phosphorus uptake and runoff losses. J. Environ. Qual. 27:1403–1410.

Gomez, K.A., and A.A. Gomez. 1984. Statistical procedures for agricultural research. 2nd ed. Wiley-Interscience, New York.

Goolsby, D., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulembach, R.P. Hooper, D.R. Kenney, and G.J. Stensland. 1999. Flux and sources of nutrients in the Mississippi–Atchafalaya River Basin. Topic 3 report for the integrated assessment on Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program, Decision Analysis Series no. 17. U.S. Dep. of Commerce, NOAA, Silver Springs, MD.

Gupta, S.C., J.K. Radke, J.B. Swan, and J.F. Moncrief. 1990. Predicting soil temperatures under a ridge-furrow system in the Corn Belt. Soil Tillage Res. 18:145–165.

Hansen, N.C., S.C. Gupta, and J.F. Moncrief. 2000. Herbicide banding and tillage effects on runoff, sediment, and phosphorus losses. J. Environ. Qual. 29:1555–1560.

Hermsmeier, L.F., L.D. Meyer, A.P. Barnett, and R.A. Young. 1963. Construction and operation of a 16-unit rainulator. USDA-ARS 41-62. USDA, Washington, DC.

Kanwar, R.S., J.L. Baker, and D.G. Baker. 1988. Tillage and split N-fertilization effects on subsurface drainage water quality and corn yield. Trans. ASAE 31:453–460.

Kladivko, E.J., G.E. Van Scoyoc, E.J. Monke, and K.M. Oates. 1991. Pesticides and nutrient movement into subsurface tile drains on a silt loam soil in Indiana. J. Environ. Qual. 20:264–270.

Klausner, S.D., P.J. Zwerman, and D.F. Ellis. 1976. Nitrogen and phosphorus from winter disposal of dairy manure. J. Environ. Qual. 5:47–49.

Laflen, J.M., M. Amemiya, and E.A. Hintz. 1981. Measuring residue cover. J. Soil Water Conserv. 32:341–343.

Logan, T.J., D.J. Eckert, and D.G. Beak. 1993. Tillage, crop and climate effects on runoff and tile drainage losses of nitrate and four herbicides. Soil Tillage Res. 30:75–103.

Logan, T.J., G.W. Randall, and D.R. Timmons. 1980. Nutrient content of tile drainage from crop land in the North Central Region. Ohio Agric. Res. Dev. Center North Central Regional Res. Bull. 268. Ohio Agric. Res. Dev. Center, Wooster, OH.

Mbagwu, J.S.C. 1989. Influence of cattle-feedlot manure on aggregate stability, plastic limit and water relations of three soils in North-Central Italy. Biol. Wastes 28:257–269.

Mueller, D.H., R.C. Wendt, and T.C. Daniel. 1984a. Soil and water losses as affected by tillage and manure application. Soil Sci. Soc. Am. J. 48:896–900.

Mueller, D.H., R.C. Wendt, and T.C. Daniel. 1984b. Phosphorus losses as affected by tillage and manure application. Soil Sci. Soc. Am. J. 48:901–905.

Munyankusi, E., S.C. Gupta, J.F. Moncrief, and E.C. Berry. 1994. Earthworm macropores and preferential transport in a long-term manure applied Typic Hapludalf. J. Environ. Qual. 23:773–784.

Olsen, T.C., and L.S. Schoeberl. 1970. Corn yields, soil temperature, and water use with four tillage methods in the western Corn Belt. Agron. J. 62:229–232.

Payne, G.A. 1994. Sources and transport of sediment, nutrients, and oxygen demanding substances in the Minnesota River Basin, 1989–1992. *In* Minnesota River Assessment Project Rep., Vol II: Physical and Chemical Assessment. Minnesota Pollution Control Agency, St. Paul.

Randall, G.W., and T.K. Iragavarapu. 1995. Impact of long-term tillage systems for continuous corn on nitrate leaching to tile drainage. J. Environ. Qual. 24:360–366.

Randall, G.W., T.K. Iragavarpu, and M.A. Schmitt. 2000. Nutrient losses in subsurface drainage water from dairy manure and urea applied for corn. J. Environ. Qual. 29:1244–1252.

Rehm, G., M. Schmitt, and R. Munter. 1993. Fertilizing corn in Minnesota. Publ. AG-FO-3790-B. Minnesota Ext. Serv., Univ. of Minnesota, St. Paul.

SAS Institute. 1994. SAS user's guide and SAS procedures guide. SAS Inst., Cary, NC.

Sharpley, A., J.J. Meisinger, A. Breeuwsma, J.T. Sims, T.C. Daniel, and J.S. Schepers. 1998. Impacts of animal manure management on ground and surface water quality. p. 173–242. *In* Hatfield and Stewart (ed.) Animal waste utilization: Effective use of manure as a resource. Ann Arbor Press, Chelsea, MI.

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. J. Environ. Qual. 27:277–293.

Sutton, A.L., D.W. Nelson, D.T. Kelly, and D.L. Hill. 1986. Comparison of solid vs. liquid dairy manure application on corn yield and soil composition. J. Environ. Qual. 15:370–375.

USEPA. 1981. Procedures for handling and chemical analysis of sediment and water samples. U.S. Environ. Lab., U.S. Army Engineer Water Ways Exp. Stn., Vicksburg, MS.

USEPA. 1986. Quality criteria for water. Office of Water Regulation and Standards, USEPA Rep. 440/5-86-001. U.S. Gov. Print Office, Washington, DC.

USEPA. 2000. Current drinking water standards [Online]. Available at http://www.epa.gov/safewater/mcl.html (verified 1 Dec. 2000).

Wagenet, R.J., J.W. Biggar, and D.R. Nielsen. 1977. Tracing the transformations of urea fertilizer during leaching. Soil Sci. Soc. Am. J. 41:896–902.

Wendt, R.C., and R.B. Corey. 1980. Phosphorus variation in surface runoff from agricultural lands as a function of land use. J. Environ. Qual. 8:387–392.

Wheaton, R.Z. 1977. Drainage needs of the upper Midwest. ASAE Paper no. 77-2086. Am. Soc. Agric. Eng., St. Joseph, MI.

Young, R.A., and R.F. Holt. 1977. Winter-applied manure: Effects on annual runoff, erosion, and nutrient movement. J. Soil Water Conserv. 32:219–222.

Young, R.A., and C.K. Mutchler. 1976. Pollution potential of manure spread on frozen ground. J. Environ. Qual. 5:174–179.

Zhao, S.L. 1998. Water, sediment, and nutrient transport from a tile drained soil with surface inlets. Ph.D. thesis. Diss. Abstr. 98-34960. Univ. of Minnesota, St. Paul.